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Modification of the coherence properties of a laser beam by a plasma

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Abstract

Spatial and temporal coherence is a fundamental property of laser beams. This peculiar quality is a problem for laser fusion because it induces spatial non uniformities of the laser intensity in the focal spot and it generates coherent coupling between the electromagnetic laser wave and the plasma waves. In the past many years, it has been shown that laser beam smoothing using different techniques (random phase plate, smoothing by spectral dispersion, polarisation smoothing, ...) can reduce parametric and hydrodynamic instabilities which are detrimental processes to Inertial Confinement Fusion (ICF). More recently, it has been predicted theoretically [1] and numerically [2-4] that the laser beam coherence properties can be modified by the propagation of the laser beam through an underdense plasma. Recent experiments with the six-beam LULI laser facility demonstrate the effectiveness of this process through different diagnostics, give insight on its origin, and show some of its consequences on parametric instabilities.

1. Introduction

Both in indirect and direct drive, the laser beams will propagate through long underdense plasmas before they interact with the high density plasma. It is of fundamental importance for inertial confinement fusion (ICF) to understand and to control the non linear processes which can affect the laser beams during their propagation. The three major concerns for ICF are the good uniformity of irradiation, the high efficiency of the laser-plasma coupling and the limitation of the number of high energy electrons. Most of the detrimental processes, such as stimulated Brillouin and Raman scattering, filamentation and self-focusing of the laser light, have been identified a long time ago. Optical smoothing techniques, which increase spatial and temporal incoherence of the laser beams, have been proposed and implemented to reduce the growth of these non-linear processes [5].

In addition to such smoothing, recent theoretical studies have suggested [1-4] that the propagation of the intense laser beam through the underdense plasma could also induce large spatial and temporal incoherence in the beam itself. A first evidence of the smoothing of the random phase plate intensity distribution of a laser beam after propagation through a preformed plasma had been obtained from time and space-resolved pictures of the far field transmitted light [6]. This so-called "plasma-induced incoherence" (PII) results from the non linear interaction between the laser beam and the plasma. Increase of the incoherence of the propagating beam is produced by the coupling between forward Brillouin scattering and self-focusing inside the speckles of an incident spatially randomised beam. The resonant instability of non linear filaments can also play an important role in plasma induced beam smoothing. The spatial incoherence is characterised by the decrease of the effective beam f-number, while the temporal incoherence is associated with a reduction of the correlation time, both features occur along the propagation direction. Increase of spectral bandwidth and of angular divergence of a laser beam has been reported before [7]. This modification of the characteristics of a laser beam propagating through a plasma can have important implications to ICF : beam spray may affect the initial irradiance symmetry and beam incoherence can reduce parametric instabilities.

In this paper, we present new results on the modification of the coherence properties of a laser beam obtained with the six-beam LULI laser facility. Evidence of induced incoherence has been obtained from the diffraction pattern of an object placed in the interaction beam and from the temporal evolution of the angular spreading of the transmitted beam. The temporal coherence of the beam has been measured with a Michelson interferometer. Further evidence of of induced incoherence is the large spectral broadening of the laser beam after its propagation through the plasma which has been correlated with the large angular spreading . Ion acoustic waves, having a small wave vector transverse to the interaction beam, have been observed, using Thomson scattering of a short wavelength laser beam These waves are strongly dependent upon the laser intensity and the plasma electron density, and are likely to be involved in the plasma smoothing as they are clearly correlated with the large red-shifted component of the transmitted beam.

2. Laser beam configuration and diagnostics

The experiment was performed using the six beams of the LULI laser facility. Fig. 1 shows the experimental setup. The laser beam configuration and plasma formation was as follows. The 600ps FWHM Gaussian beams were all in the same plane and arrived at the target at different times : two 0.53μm plasma producing beams at t=0, a 0.53μm plasma heating beam at t=0.5 ns, the 0.35μm Thomson scattering probe beam and the 1.05μm interaction beam at t=1.6 ns. Random phase plates (RPP) were used on the beams producing and heating the plasma to obtain interaction conditions as reproducible as possible. The interaction beam was focused with an f/6 lens through an RPP of 2mm square elements. The resulting focal spot diameter was 320μm (FWHM) with a focal depth of 1.5mm. The average intensity in the focal spot was 10^{14}W/cm^2. The targets were 400μm diameter, 1.2μm thick, $(CH)_n$ disks.

The transmitted light was collected with an f/3 lens (twice the aperture of the focusing lens) and sent to four different stations : a 2D imaging system with or without temporal resolution, a Michelson interferometer and a spectrometer coupled to a streak camera. Light was also collected at 22.5° from the axis of the interaction beam in the forward direction to provide time-resolved spectra at a larger angle than the previous ones (not shown on the figure). Thomson scattering of the 3ω probe beam was used in a number of ways to measure : a) the amplitude and the location of the ion acoustic waves associated with stimulated Brillouin scattering, b) the electron plasma waves associated with stimulated Raman scattering, and c) ion acoustic waves having a small wave vector transverse to the interaction beam. In the first two cases, the scattered light was collected by a parabolic mirror. In the third case, the light was collected by an f/3 lens with a mask to stop the direct incident probe light. In all cases, the plasma was imaged on the slits of the spectrometers which were coupled to streak cameras.

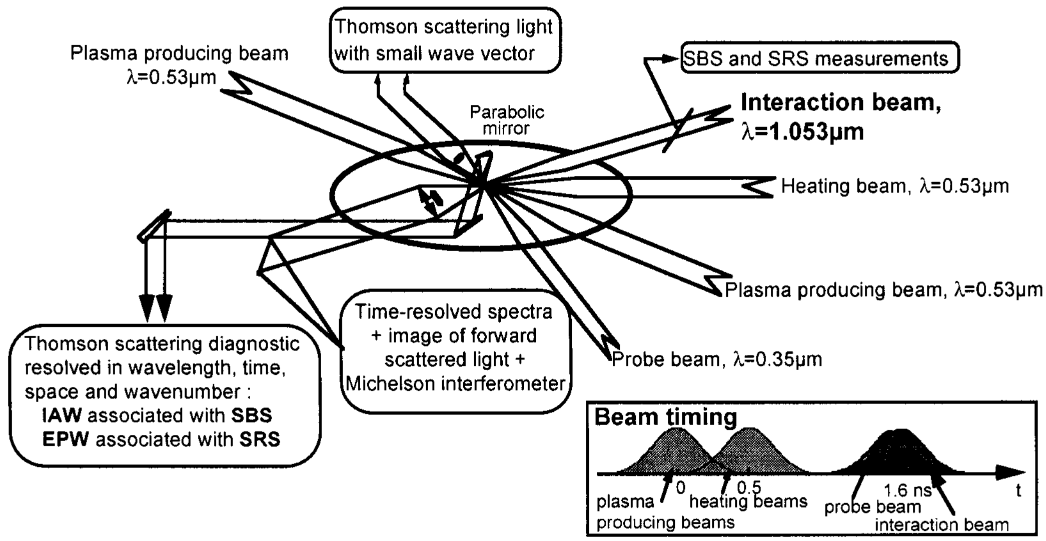

Figure 1 : Experimental set-up showing the beam configuration and part of the diagnostics.

At the time of interaction, the plasma had a density profile with an approximately inverse parabolic shape along the laser direction with a scalelength of ~1mm. The maximum electron density evolved from 25% to 8% of critical density ($n_c = 1.1 \times 10^{21}$ cm^{-3} is the critical electron density for λ_0=1.05μm light) during the interaction pulse. For some experiments a plasma with a higher electron density was used, but the results will not be presented in this paper. The electron temperature was ~ 0.7keV at the peak of the interaction pulse.

3. Results showing the plasma induced incoherence of the laser beam

The first evidence of the decrease of the coherence of the laser beam had been obtained from the diffraction patterns of an object in the beam after its propagation through the preformed plasma. The object was the random phase plate of the interaction beam placed in front of the focusing lens. The diffraction patterns, without and with the plasma, are shown in Fig.2. These images are integrated over ~200 ps around the peak of the pulse.

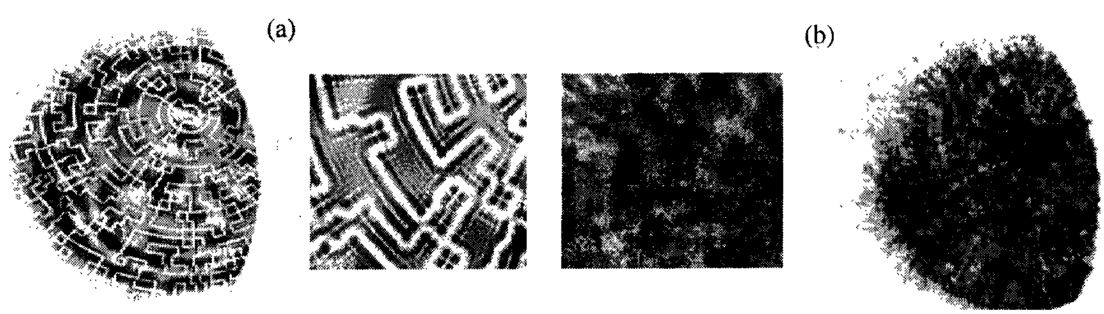

Figure 2 :Diffraction patterns of the random phase plate,
placed in front of the focusing lens of the interaction beam,
(a) *after propagation through vacuum ;(b) through the preformed plasma.*

The diffraction fringes produced by the edges of each element of the RPP are very clear after propagation through vacuum and become blurred when propagating through the plasma when at high laser intensities. This blurring can be interpreted by the superposition of slightly shifted patterns produced by enhanced angular spreading of the laser light. One can still see some imprint of the RPP in Fig2-b. The blurring is not due to beam steering, but to a true loss of coherence.

The angular spreading of the laser beam after propagation through the preformed plasma was obtained with a Gated Optical Imager (GOI). The temporal evolution of 2D images of the near field pattern of the transmitted beam is shown in Fig. 3. Each image is integrated over 80 ps. The first one, Fig. 3-a, was recorded during the first part of the laser pulse and the second one, Fig. 3-b, was recorded during the second part of the laser pulse. One can see a clear increase of the angular distribution, by a factor ~1.5, late in time.

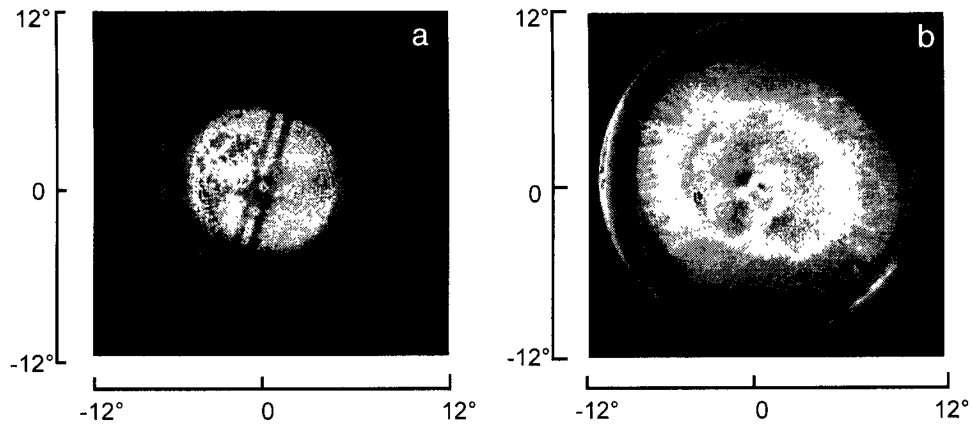

Figure 3 : Angular diagram of the transmitted light
a) during the first part of the laser pulse ; b) during the second part of the laser pulse

The temporal coherence of the laser beam after propagation through the plasma has been studied using a Michelson interferometer. Light was collected in the forward direction, outside the incident cone. The interference pattern was imaged onto the slit of a streak camera. Moving one of the mirrors changes the length of one of the arm of the interferometer and produces a time delay between the two pulses of light. In Figure 4 are shown interference patterns resolved in time, corresponding to delays of 0, 10 and 20 ps. Structures inside the fringes correspond to angular structures inside the transmitted beam.

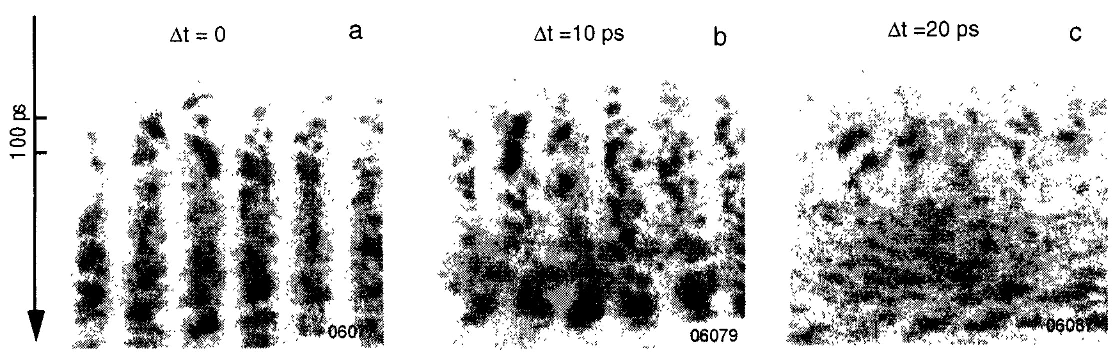

Figure 4 : Interference patterns of the transmitted light as a function of time for three time delays of the Michelson interferometer :
a) $\Delta t=0$; b) $\Delta t=10$ ps ; c) $\Delta t=20$ ps.

The fringes are very clear with no delay, and disappear rapidly when increasing the delay, to be almost completely blurred for 20 ps. With no plasma, the blurring of the fringes with a time delay of 20 ps is almost imperceptible, which demonstrates induced temporal incoherence due to the propagation in the plasma. Figure 4-b shows the distortion of the fringes as a function of time, which also means as a function of laser intensity, as the laser pulses are Gaussian in time. The time delay for which the blurring appears decreases with the laser intensity, plasma density and angle of observation.

Another sign of the temporal incoherence of the transmitted beam is its large spectral broadening as shown in Figure 5. On the top of the large broadening, a large red-shift is also observed. This shift is more than ten times larger than the one which would be expected from forward stimulated Brillouin scattering. This red-shifted spectrum displays a non-linear behavior : its shift, width, duration and amplitude all increase with incident intensity.

As a consequence of the plasma induced incoherence, the laser intensity spatial distribution was smoothed due to its non linear propagation. 2D images of the intensity distribution inside the focal spot are shown in Figure 6, in the vacuum and with a plasma. The traces show a strong reduction of the amplitude of the intensity fluctuations in the plasma.

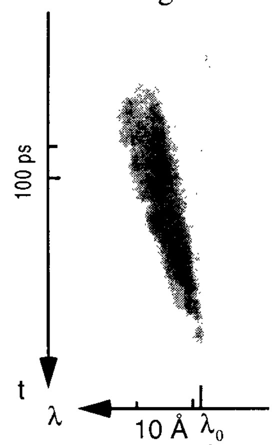

Figure 5 : Time-resolved spectrum of the transmitted light collected at 9±1° from the laser axis

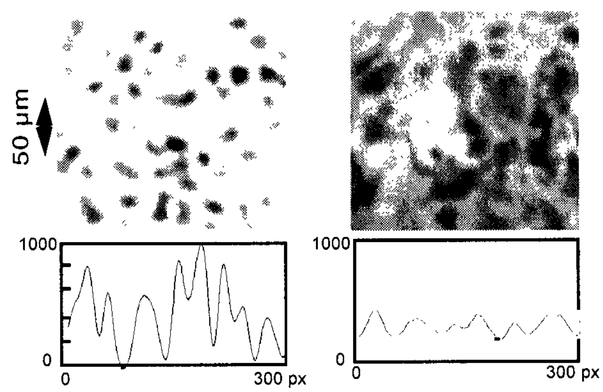

Figure 6 : 2D images of the spatial intensity distribution in the focal plane :
a) in the vacuum ; b) with the preformed plasma

4. Origin of the plasma induced incoherence

The theoretical interpretation of plasma induced smoothing is the following [4] : in the regime where the average power in a speckle approaches the self-focusing threshold, laser filaments forms and the high intensity filaments are unstable. This instability corresponds to forward SBS growing inside the cavity formed by the density depletion associated with the filament. Following this interpretation, we set up a Thomson scattering diagnostic to look for ion acoustic waves having wavenumbers satisfying the coupling relations of forward SBS. An example of time-resolved spectrum of the Thomson scattered light at an angle of 6° from the axis of the probe beam is shown in Fig. 7. We observed only one component, slightly red-shifted from the probe wavelength, which occurred during the second part of the laser pulse. This scattered light demonstrates the presence of ion acoustic waves with small wave numbers transverse to the interaction axis. We studied this emission in detail as a function of the laser intensity, the plasma density, and this will be presented in another paper. One important result is that the scattered light intensity correlated very well with the intensity of the red-shifted component of the transmitted light. This demonstrates the participation of ion acoustic waves in plasma induced incoherence.

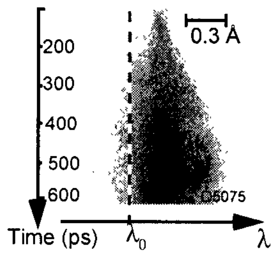

Figure 7

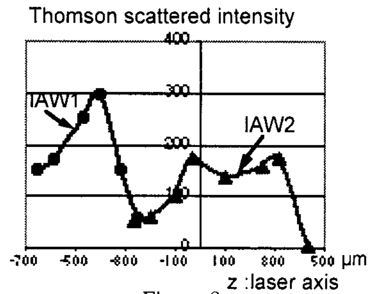

Figure 8

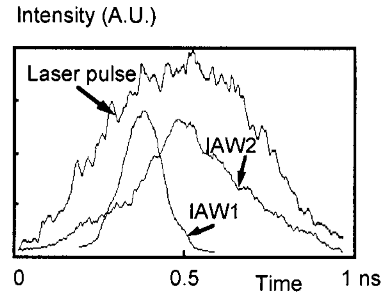

Figure 9

Figure 7 : Time-resolved spectrum of theThomson scattered light off ion acoustic waves with small wave numbers transverse to the interaction axis.

Figure 8 : Location of the ion acoustic waves associated with backward SBS (circles) and with plasma smoothing (triangles) in the density profile.

Figure 9 : Timing of the ion acoustic waves associated with backward SBS (IAW1) and with plasma smoothing (IAW2) relative to the incident laser pulse.

5. Consequences of the plasma induced incoherence on parametric instabilities

The plasma induced incoherence is predicted to have a strong effect on parametric instabilities [4]. Our preliminary results show some anticorrelation between the location in the density profile along the laser propagation axis of the ion acoustic waves associated with backward SBS and the ion acoustic waves associated with plasma smoothing (Fig. 8). They also show that the ion acoustic waves associated with backward SBS disappear in time when the ion acoustic waves associated with plasma smoothing start to grow (Fig. 9). This may be the first experimental evidence of the hindrance in space and time to the backward SBS due to plasma smoothing.

6. Conclusion

We have presented results based on different diagnostics showing the reduction of the spatial and temporal coherence of a laser beam after propagating through a plasma. This effect has important implications concerning the growth of parametric instabilities in laser fusion.

Acknowledgments

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